SCALED EXPERIMENTS TO STUDY VAPOUR CLOUD EXPLOSIONS

D.M. Johnson, P. Sutton and M.J. Wickens
British Gas, Research and Technology Division, Midlands Research Station, Solihull, West Midlands, B91 2JW.

Large scale experiments carried out by British Gas have demonstrated that only under particular conditions where flammable mixture engulfs closely packed obstacles, can high flame speeds be sustained in natural gas-air vapour clouds. Such high speed flame propagation can be reproduced at reduced scale by using oxygen enrichment to overcome turbulence quenching effects. This scaling technique has been used to conduct a parameter study of conditions which can sustain high flame speeds in arrangements of repeated pipework obstacles.
Explosions/Natural Gas/VCE/Scaling/Obstacles/Experiments

1. INTRODUCTION

The accidental release of a flammable gas or vapour into the atmosphere can lead to the formation of a flammable cloud. If ignited, the combustion of such a cloud can result in the generation of damaging overpressures, such as occurred at Flixborough in 1974(1), following the release of approximately 40 tonnes of cyclohexane. These events have become known as vapour cloud explosions.

The magnitude of the overpressure generated by the combustion of a flammable vapour cloud in the atmosphere, is related to the speed of propagation of the flame(2). In order to generate overpressures high enough to result in major structural damage to plant or buildings, a flame needs to reach high speeds (>120 ms^{-1}) as it propagates through the cloud. Previous work by British Gas(3) and other organisations(4,5,6) has shown that although the low energy ignition of quiescent flammable vapour clouds results only in flame speeds of a few metres per second, the presence of pipework obstacles within a flammable vapour cloud can lead to significant flame acceleration. Large scale experiments(3) have also demonstrated that under particular conditions a flame jetting from a confined region into a cloud which engulfs a region of piperack congestion, can result in high speed flame propagation and high overpressures.

To assess the potential for vapour cloud explosions to occur within regions of process pipework, it is necessary to have information on how the configurations of such regions influence the ability to sustain a high speed flame. This information could be provided by an extensive parameter study, but for this to be conducted at large scale would be prohibitively expensive. A more practical approach is to conduct experiments at smaller scale, provided that the results obtained can be applied to the large scale situation. However, scale dependent combustion processes mean that flame speeds and overpressures generated in small scale natural gas-air experiments will not reproduce large scale combustion behaviour unless action is taken to overcome these scale effects.

This paper discusses small scale experiments undertaken to assess the influence of various parameters on the ability of idealised piperack structures to sustain high speed flame propagation. Oxygen enrichment was used to overcome scale dependent combustion processes. The experiments were carried out in a test enclosure which was a 1/5th scale replica of a 45m long, 3m square cross-section rig used in earlier large scale experiments.

2. VALIDATION OF SCALING TECHNIQUE

Before it was possible to carry out a small scale parameter study, the scaling technique had first to be validated against results obtained from large scale experiments. This section describes the large and small scale experiments conducted to determine the degree of oxygen enrichment required to overcome the effects of the scale dependent combustion processes.

2.1 Large Scale Experiments

The large scale experimental enclosure which had been used in the earlier study(3) is shown Figure 1. It consisted of a 9m long, 3m square cross-section confined region and a 36m long polythene covered region of external congestion. Arrays of obstacles formed from 180mm diameter pipe were located at intervals throughout the length of the enclosure. Within and just outside the confined region these arrays had an area blockage of 42% (defined as the 'blocked' area as a percentage of the total cross-sectional area) and were spaced at 1.5m intervals. The tests were ignited within the confined region, which generated, in natural gas-air tests, a flame which emerged into the polythene covered part of the test enclosure at a speed of typically 500 ms^{-1}.

Typical flame speed-distance and overpressure-time plots measured in a large scale natural gas experiment are shown in Figures 2a and 2b respectively. The above blockages extended the full length of the test rig. The flame speed-distance profile shows that the rate of flame propagation through the congested region was not uniform. These variations were caused by the interaction of the flame with the obstacle arrays. The lowest speeds were produced just upstream of each array and the highest speeds just downstream of each array. The pressure-time profile consisted of a lead shock with a magnitude of over 3 bar, followed by a pressure peak generally 3 to 4 bar in magnitude but which incorporated short duration pressure spikes of over 6 bar.

The high speed mode of combustion observed in the natural gas-air experiments involves the coupling of the flame front with a shock front which propagates a short distance ahead of the flame. This coupling of flame and shock could be sustained only if there was a sufficient degree of pipework obstruction within the natural gas-air mixture. If the flame emerged from such a congested region into an unobstructed part of the vapour cloud, or the degree of pipework obstruction dropped below a certain threshold level, rapid flame deceleration occurred. Once the flame had de-coupled from the shock front, high speed flame propagation could be re-initiated only if the flame encountered another confined region or a region of sufficiently densely packed obstacles. In this respect, it is important to note that in the absence of confinement, the large scale experiments indicated that the degree of pipework obstruction required to generate a high speed flame was significantly greater than that which would sustain a flame already propagating at high speed.

2.2 Small Scale Test Enclosure

The small scale experiments were conducted in a 1/5th scale replica of the large scale enclosure which is shown in Figure 3. Within the congested region, pipework obstacles were supported on a framework formed from longitudinal mild steel bar as shown in Figure 4. This technique provided a flexible arrangement for supporting the obstacles, allowing many parameter changes to be studied, e.g. pipe size, blockage ratio and blockage configuration. The polythene sheet used to cover the congested region was supported on steel arches 0.3m beyond the obstacle supports. This arrangement gave a similar external blockage along the sides of the test rig, as that provided by the obstacle supports used in the large scale test enclosure.

2.3 Scaling Technique

The objective of the small scale experiments was to reproduce the mode of flame propagation that had been observed in the large scale natural gas-air tests. To achieve this objective, the flame speeds in the small scale test enclosure had to be the same, at all scaled positions, as those in the large scale tests. As a result, the overpressures generated would have a similar magnitude and shape to the overpressures generated in the large scale tests, but would have only one fifth of the duration of the large scale results.

Experiments conducted in the small scale rig using natural gas-air did not reproduce the high speed mode of combustion observed at large scale, with flame speeds generated in the small scale rig being only about 40 ms^{-1}. The dominant effect on combustion which results in these lower flame speeds and overpressures in the small scale tests, is turbulence quenching. It has been proposed(7) that the main parameter controlling turbulence quenching in natural gas-air mixtures, is the Karlovitz number (the ratio of the chemical time of combustion to the time scale associated with turbulence). In small scale experiments, due to the reduced size of all the obstacles, the time scale associated with turbulence is reduced. Thus for a given gas-air mixture, this results in a greater propensity for turbulent flame quenching to occur.

One method of overcoming turbulence quenching in the small scale experiments is to reduce the chemical time scale of combustion by the same factor as the time scale associated with turbulence, thus preserving the Karlovitz number. Reduction of the chemical time scale in these experiments was achieved by oxygen enriching the natural gas-air mixture. The degree of oxygen enrichment is defined as the concentration (v/v) of oxygen in the non-natural gas components of the mixture.

2.4 Selection of Oxygen Enrichment

The oxygen enrichment which would most closely reproduce the large scale results in the small scale rig, was chosen using an obstacle configuration which involved gradually increasing the distance between successive obstacle arrays along the length of the test enclosure. At large scale the obstacle arrays used had an area blockage 42% and were formed by 180mm diameter pipes, and in this configuration the high speed mode of combustion was sustained up to and including arrays spaced at 2.8m intervals.

Small scale tests were carried out in an equivalent configuration using oxygen enrichments of up to 27%. It was found that the high speed mode of combustion could be generated and sustained along at least part of the small scale test enclosure with oxygen enrichments which exceeded 24.5%. However, at an oxygen enrichment of 26.5% the maximum array spacing which would sustain a high speed flame was equivalent to that obtained in the large scale test rig. This enrichment is in reasonable agreement with the value expected from theory(7) and is specifically for reproducing the high flame speeds encountered in these experiments.

Overpressure-time profiles recorded in equivalent large and small scale tests are compared in Figure 5. The time scale of the small scale test has been increased by a factor of five so that a direct comparison of the two profiles can be made. Figure 5 shows clearly the similarity of the two overpressure-time profiles and that approximately the same magnitude overpressures were generated at both scales. The separation between the shock front and the reaction zone (marked on Figure 5) is also approximately the same in the two experiments.

3. PARAMETER STUDY

The scaling technique was used to undertake a parameter study in the small scale rig to determine the minimum number of horizontal obstacles, positioned perpendicular to the the long axis of the test rig and therefore the direction of flame propagation, which would sustain a high speed flame. In these tests, the "standard" obstacle configuration of 42% area blockage arrays spaced at 0.3m intervals, was always used in the confined region and the first 1.8m length of the external polythene covered congested region. This was to ensure that the high speed flame was initiated in the same manner in each experiment. Experiments were performed to study the effects of parameter changes including, oxygen enrichment, obstacle diameter, the area blockage of each obstacle array, blockage distribution and blockage on the sides of the congested region, an increase in the cross-sectional area of the congested region and also the effect of a 90° change in direction of the congested region.

3.1 Effect of Obstacle Array Area Blockage and Pipe Diameter

Experiments were performed using obstacle arrays formed by horizontal 20mm, 36mm and 63mm o.d. pipes placed perpendicular to the direction of flame propagation. The range of area blockages used was between 21% and 63%. Figure 4 shows a typical arrangement of an array, in which seven horizontal 36mm o.d. pipes were used to give an area blockage of 42%. For each area blockage used, tests were carried out in which the spacing between the arrays was increased, until an array spacing was reached which would not sustain a high speed flame.

The results from these experiments are shown in Figure 6, where the maximum array spacing which would sustain a high speed flame is plotted against area blockage. For obstacle array spacing/area blockage combinations which lie below the curves plotted on Figure 6, high speed flame propagation was sustained. This was not sustained for combinations which lie above the curves. Figure 6 shows that as the area blockage of the arrays was increased, the maximum array spacing which could sustain a high speed flame also increased.

There is reasonable agreement between the results obtained with all the diameters of pipes used, with the same trend of increasing maximum array spacing with increasing array area blockage. However, in tests with the 20mm diameter pipes, the maximum array area blockage used was only 40%.

3.2 Volume Blockage

The results from the experiments described in Section 3.1 above have been presented on the basis of the area blockage and the spacing between successive arrays. However, these experiments can also be interpreted in terms of a volume blockage, defined as the percentage of the total volume of the congested region which is taken up by pipework obstacles. The minimum volume blockage required to sustain a high speed flame in any given configuration is a single descriptive parameter of the obstructed region and offers the potential of characterising regions of less idealised arrangements of random sized process pipework such as would occur in practice.

Figure 7 shows the dependence of the minimum volume blockage to sustain a high speed flame on both array area blockage and pipe diameter. It can be seen that, for the high speed mode of flame propagation obtained in these experiments, volume blockage does not provide a single descriptive parameter as there is a dependence upon array area blockage and, most notably, pipe diameter. Overall the minimum volume blockage to sustain a high speed flame varied between 1.7% and 8%.

Figure 7 does, however, show that for both 36mm and 63mm diameter pipes, the number of obstacles required to sustain a high speed flame is at a minimum when the array area blockage is 42%.

3.3 Effect of Blockage on the Outside of the Congested Region

Experiments have been performed to assess the effect of blockage along the sides and top of the congested region, on the maximum obstacle array spacing which can sustain a high speed flame. The external blockage was provided by either plywood sheets or 32mm o.d. pipes in line with the direction of flame propagation, fixed along the sides and/or the top of the congested region, as shown in Figure 8. Thirteen longitudinal 32mm o.d. pipes were fitted to the top of the congested region and either seven or eleven pipes to the sides. These gave perimeter area blockages of 41% or 64% on the sides and 69% on the top. For all these tests, the obstacle arrays within the congested region were formed from 36mm o.d. pipes, arranged in arrays of 42% area blockage. The tests were conducted by increasing array spacings until the maximum array spacing which would sustain a high speed flame was attained.

The results are given in Table 1 and show that the presence of blockage on the perimeter of the congested region, increased the maximum spacing between arrays which would sustain a high speed flame. With complete blockage on either one side or the top of the congested region, the array spacing which would sustain a high speed flame was increased by about a quarter. In experiments with perimeter blockage provided by 32mm pipes, the higher value of perimeter blockage also gave an increase in array spacing of about a quarter, whereas the lower value of perimeter blockage gave only a 15% increase in array spacing. These results indicate that high levels of blockage on the outside surfaces of a piperack region are required in order to increase significantly the maximum obstacle arrays spacing which can sustain a high speed flame.

3.4 Effect of a 90 Degree Bend in the Congested Region

A number of tests were performed to study the effect of a 90° change of direction of the congested region, as shown in Figure 9. The obstacle configuration in the first half of the congested region before the bend consisted of 36mm o.d. pipework obstacle arrays of 42% blockage, spaced 0.3m apart. To study the obstacle configurations which would sustain high speed flame propagation around the bend, two parameters were varied separately. Firstly, the distance between the side of the congested region prior to the bend and the first obstacle array after the bend (distance d on Figure 9) was varied, with the distances between all the remaining obstacle arrays being fixed at 0.3m. Secondly, with d fixed at 0.145m, the spacing between arrays (distance s on Figure 9) was varied. In both cases, tests were carried out in which the spacings were gradually increased until high speed flame propagation was not sustained.

Table 2 compares the maximum spacings which would sustain a high speed flame in these tests, with the values obtained from tests performed without a change of direction in the congested region. The results suggest that the conditions required to sustain a high speed flame around a bend in a congested piperack are similar to those required to sustain a flame propagating along a straight piperack. This result might be expected as the shock front generated by the flame propagates in all directions and could thus retain the coupling of shock and flame even if there are changes in direction of the piperack.

3.5 Effect of Change of Cross Sectional Area

A number of tests were performed in which the cross-sectional area of the congested region was increased, as shown in Figure 10. Both the height and width of the congested region were increased from 0.6m to 1.05m at a point 1.8m into the external polythene covered region. To ensure that a high speed flame was established over the full area following the increase in cross-section, the first three or five obstacle arrays were always of 42% blockage, spaced 0.3m apart. These initial arrays were of the same pipe diameter as the pipes in the remaining congested region, either 36mm or 63mm. The configuration of subsequent pipework obstacles was then varied in order to determine the influence of cross sectional area on the maximum array spacings which would sustain a high speed flame. Because of the reduced length of the effective test section of the rig, it was found to be difficult to determine when flame deceleration occurred. For these tests therefore, the length of the test section was increased by an additional 7.2m (see Figure 10)

The maximum spacings between obstacle arrays of 42% area blockage which would sustain a high speed flame, where there was either a sudden change or a gradual change of array spacing along the congested region, are shown in Table 3 for tests carried out with both 36mm and 63mm o.d. pipes, and compared with the equivalent spacings obtained in the smaller cross sectional area tests. The results show that increasing the height and width of the congested region by 75%, approximately doubled the maximum array spacing which would sustain a high speed flame. This increase is probably due to the longer time taken for rarefaction waves which result in the decay of the shock front, to propagate from the edge of the piperack to the central region of the piperack.

The minimum values of volume blockage which would sustain a high speed flame for both cross sectional areas are also shown in Table 3. For the 36mm diameter pipes, the minimum volume blockage required to sustain a high speed propagating flame was as low as 1.03% when the array spacings were changed gradually. As for the test results discussed previously, these data indicate that a change in the geometry of the congested region results in a different value of volume blockage which is required to sustain a high speed flame.

Two experiments were performed in which three rows of 63mm diameter obstacles occupied only the top or bottom half of the increased cross-sectional area congested region, as shown in Figure 11. The results from these tests are also shown in Table 3. Although the maximum spacing which would sustain a high speed flame was reduced compared to the tests performed with the obstacle arrays located over the whole of the increased cross-sectional area, the maximum array spacings which would sustain a high speed propagating flame were still greater than in the 0.6 x 0.6m test rig.

3.6 Sensitivity to Oxygen Enrichment

To assess the sensitivity of the results obtained from the parameter study to the degree of oxygen enrichment, selected experiments were conducted at two oxygen enrichments 25.5% and 26.5%. Experiments were performed using the three pipe diameters of 20mm, 36mm and 63mm, with a sudden increase in the array spacings being made at a point 1.8m into the external polythene covered congested region. Figure 12 shows the maximum array spacing which would sustain a high speed flame, plotted against array area blockage. The maximum spacings produced in tests using the two different oxygen concentrations are compared for each pipe diameter and area blockage used. The plot shows that in the tests using the 36mm and 63mm diameter pipes, the maximum array spacing which would sustain a high speed flame was not significantly dependent on the oxygen enrichment. However, in tests using the smaller diameter pipes, there was a significant decrease in the maximum array spacing which could sustain a high speed flame with a reduced level of oxygen enrichment. Also shown on this plot is the effect of oxygen concentration on the maximum array spacing which would sustain a high speed flame with a gradual increase in the array spacings.

These results demonstrate that configurations involving gradually changing obstacle array spacings are sensitive to small changes of the oxygen content of the mixture. This sensitivity indicates that this configuration was particularly suitable for validating the scaling technique. In addition, experiments involving the smaller pipe diameters were sensitive to oxygen enrichment. This may be due to turbulence quenching resulting from the smaller scale of the turbulent eddies associated with the 20mm pipes in comparison with larger pipe diameters.

4. SUMMARY OF RESULTS AND CONCLUSIONS

A series of vapour cloud explosion experiments have been conducted to assess the influence of various parameters on the ability of idealised piperack structures, formed by repeated, regular arrays of pipes, to sustain high speed flame propagation. The experiments have been carried out in a rig at 1/5th scale, using scaling techniques to overcome scale dependent combustion processes. Consequently, the results obtained can be related to the ability for sustained high speed flame propagation to occur in a natural gas-air vapour cloud which engulfs piperacks at a scale 5 times larger. The following results have been obtained.

1. The maximum obstacle array spacing which would sustain a high speed flame increased with increasing array blockage.

2. Volume blockage does not provide a single descriptive parameter which can be used as a means of characterising the ability of piperack congestion to sustain high speed flame propagation.

3. The addition of blockage on the perimeter of the congested region increased the maximum spacing between obstacle arrays which would sustain high speed flame propagation.

4. High speed flame propagation was not significantly affected by a 90° bend in a congested region.

5. When the cross sectional area of the congested region was increased, the minimum number of obstacles which would sustain a high speed flame was reduced.

The current understanding of vapour cloud explosions involving natural gas is that combustion only of that part of the cloud which engulfs a severely congested region, formed by repeated obstacles, will contribute to the generation of pressure. However, the degree of pipework obstruction required to produce a vapour cloud explosion is as yet defined imprecisely. The results obtained from the current study provide a better definition of the range of obstacle conditions which either will or will not sustain a high speed flame in a natural gas-air cloud. Ultimately, further data of the type obtained in this study would also enable a predictive methodology for vapour cloud explosion overpressures to be developed, which could be more closely based on the precise obstacle conditions which existed within any congested region.

5. REFERENCES

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TABLE 1 : Maximum Obstacle Array Spacing to Sustain a High Speed Flame with Increased Blockage on the Perimeter of the Congested Region

	Maximum Spacing to sustain a high speed flame mm
No Perimeter Blockage	416
41% side blockage and 69% top blockage	480
64% side blockage and 69% top blockage	512
100% top blockage	512
100% side blockage	512

TABLE 2 : Maximum Obstacle Array Spacing to Sustain a High Speed Flame through a 90° Bend in the Congested Region

	Maximum Spacing with a 90° Bend mm	Maximum Spacing for Straight Congested Region mm
Maximum Value of d*	320	416
Maximum Value of s*	631	576

* See Figure 9

TABLE 3 : Maximum Obstacle Array Spacing to Sustain a High Speed Flame with an Increased Cross-Sectional Area Congested Region

A. Sudden Change of Array Spacing

Array Type	Cross-sectional Area m x m	Pipe Diameter mm	Maximum Spacing mm	Volume Blockage %
42% Area Blockage	0.6 x .06	36	416	2.85
	1.05 x 1.05	36	864	1.3
	0.6 x 0.6	63	416	5.0
	1.05 x 1.05	63	928	2.2
3 Pipes per Array in the Bottom of the Congested Region	1.05 x 1.05	36	640	1.8
3 Pipes per Array in the Top of the Congested Region	1.05 x 1.05	36	448	2.6

B. Gradually Changing Array Spacings

Array Type	Cross-sectional Area m x m	Pipe Diameter mm	Maximum Spacing mm	Volume Blockage %
42% Area Blockage	0.6 x 0.6	36	608	1.95
	1.05 x 1.05	36	1120	1.03

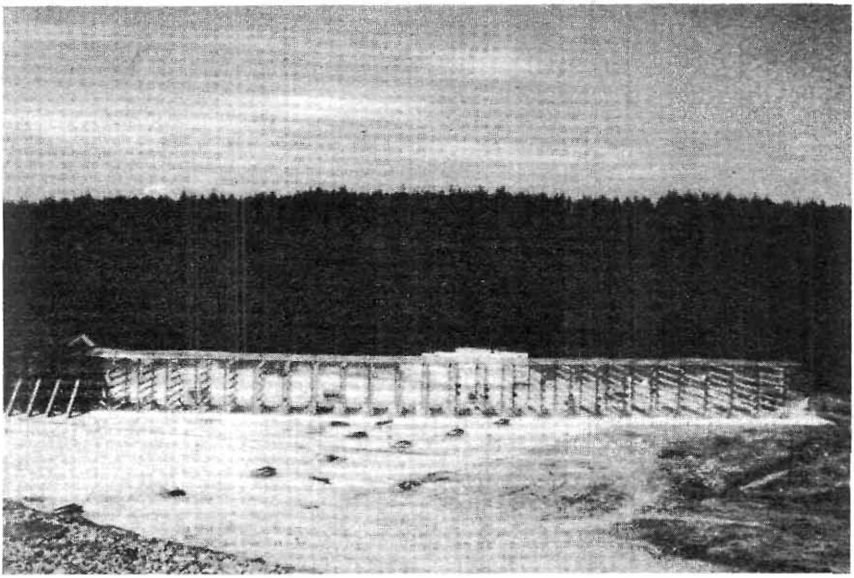


FIG 1 GENERAL VIEW OF THE LARGE SCALE TEST ENCLOSURE

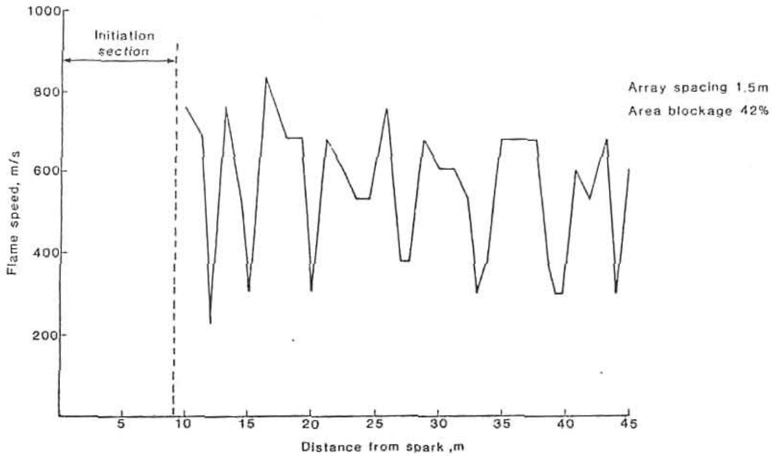


FIG 2a FLAME SPEED VS. DISTANCE PROFILE FOR A LARGE SCALE EXPERIMENT

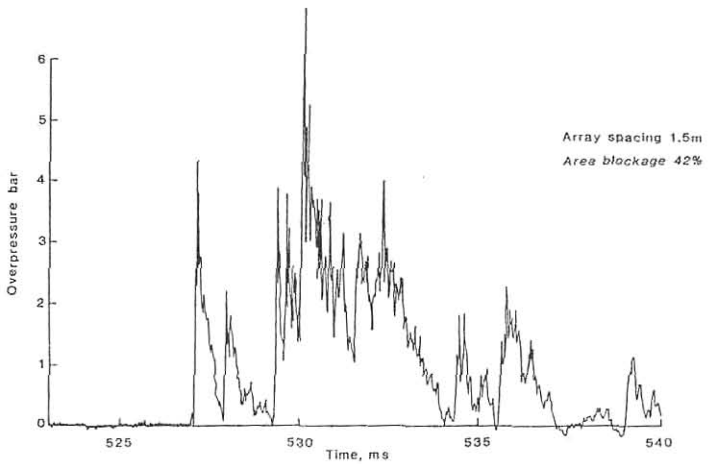


FIG 2b OVERPRESSURE VS. TIME PROFILE FOR A LARGE SCALE EXPERIMENT

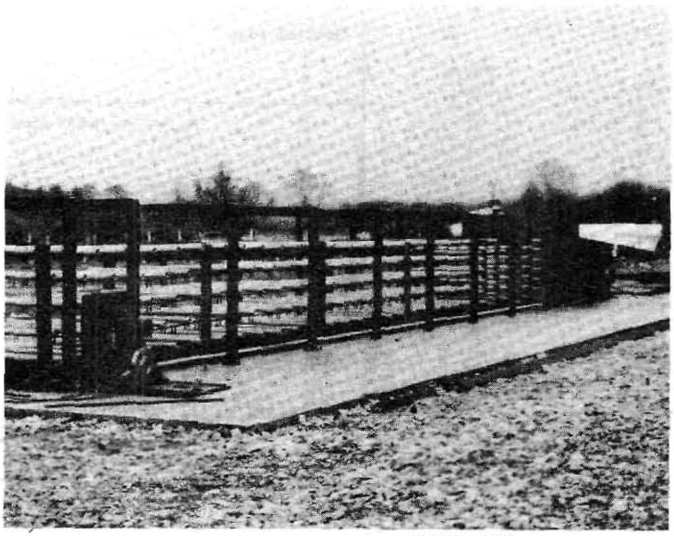


FIG 3 SMALL SCALE TEST RIG

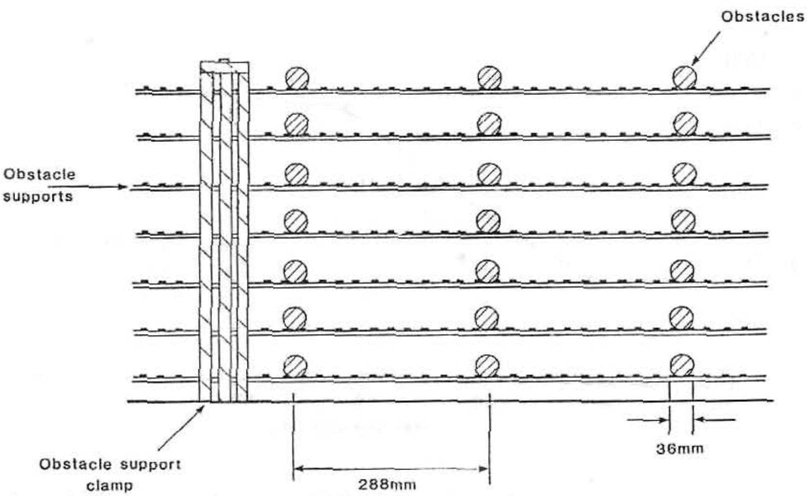


FIG 4 1/5TH SCALE OBSTACLE CONFIGURATION FOR PRELIMINARY SCALING EXPERIMENTS

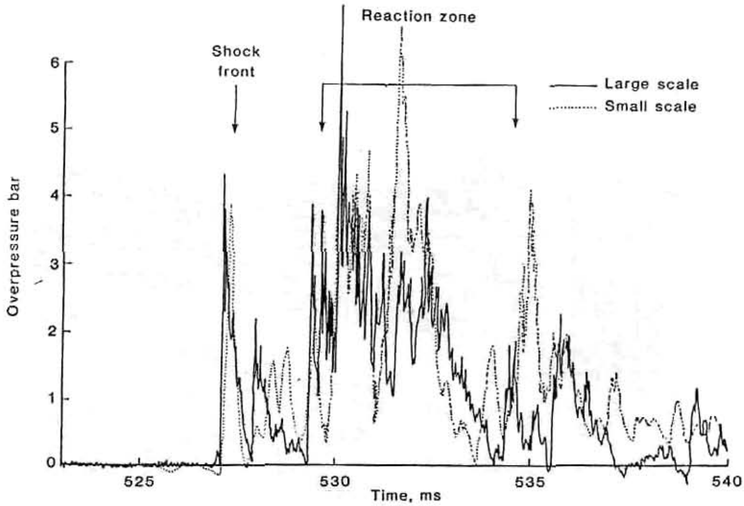


FIG 5 COMPARISON OF SMALL AND LARGE SCALE TESTS

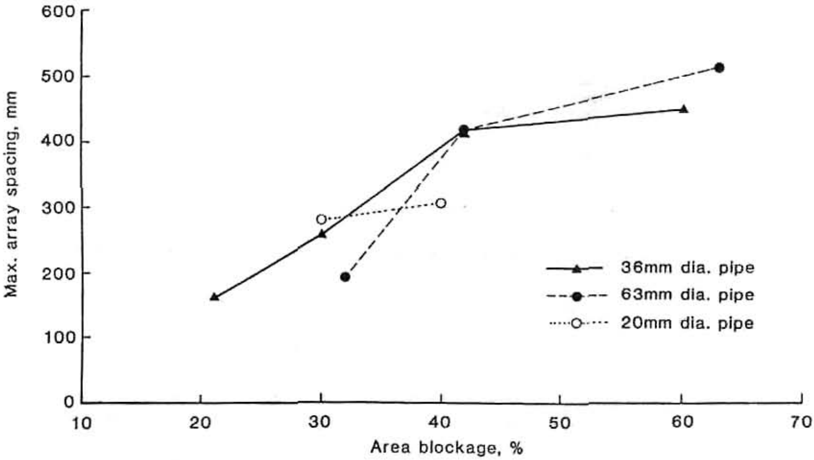


FIG 6 DEPENDENCE OF MAXIMUM ARRAY SPACING TO SUSTAIN A HIGH SPEED FLAME ON ARRAY AREA BLOCKAGE

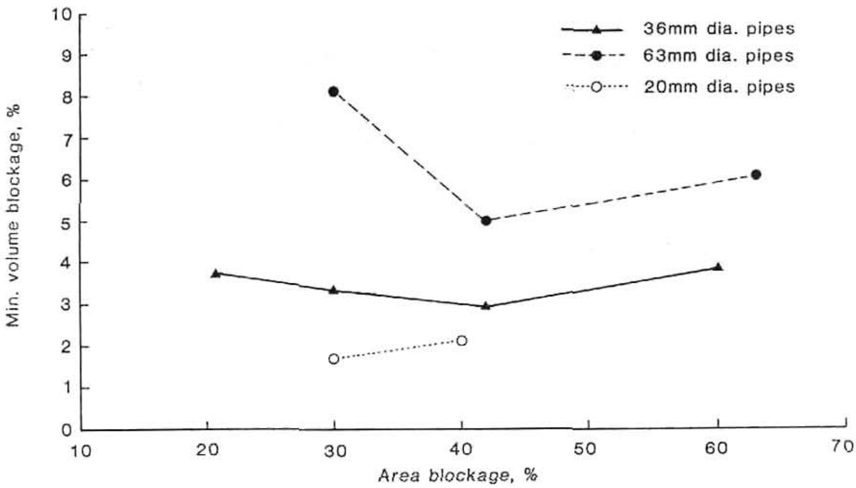


FIG 7 DEPENDENCE OF MINIMUM VOLUME BLOCKAGE TO SUSTAIN A HIGH SPEED FLAME ON ARRAY AREA BLOCKAGE

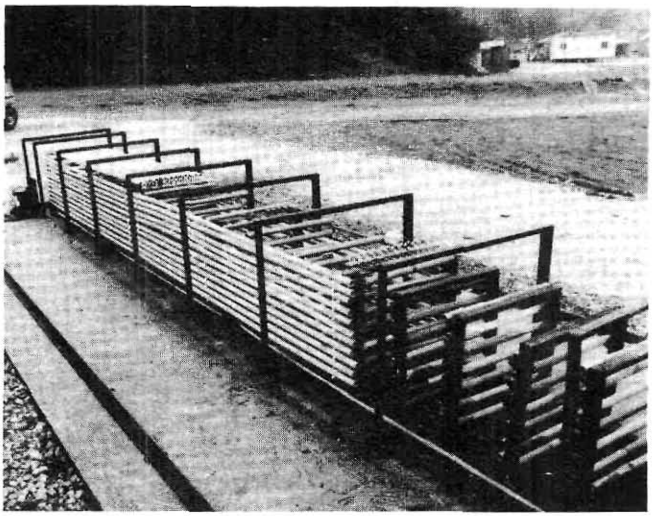
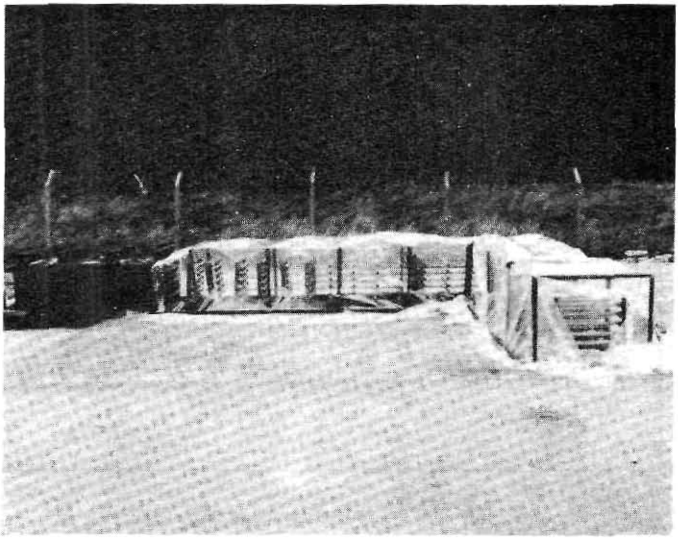
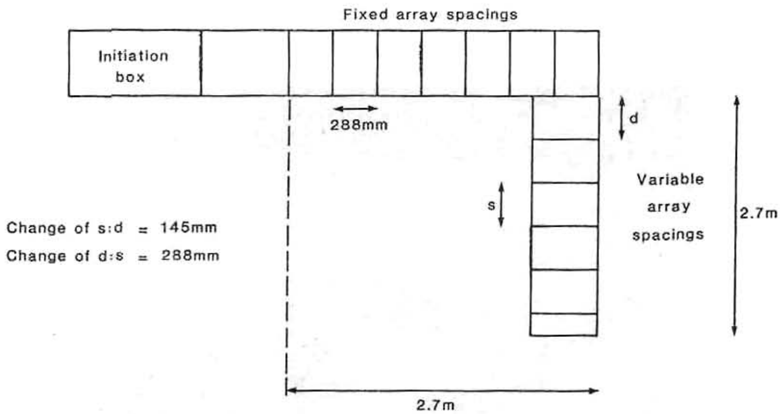


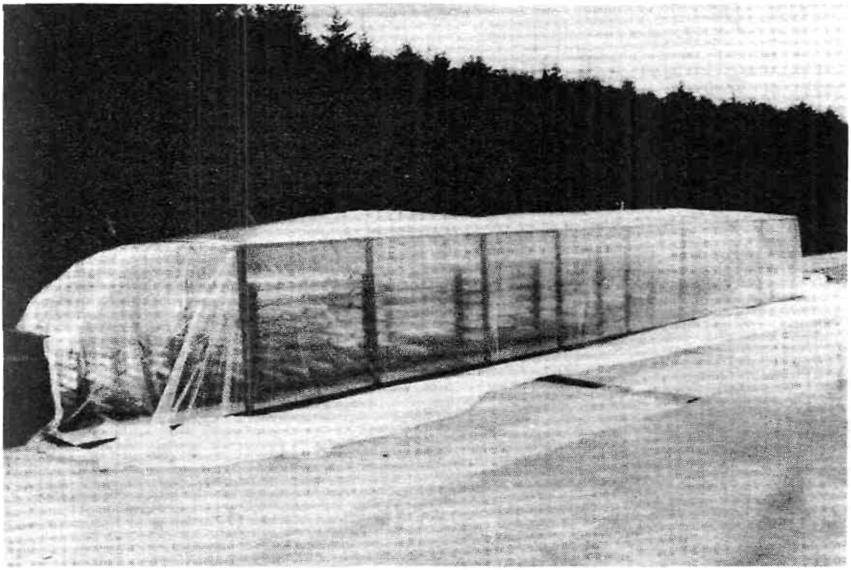
FIG 8 PHOTOGRAPH OF THE ENCLOSURE DURING FITTING OF LONGITUDINAL OBSTACLES





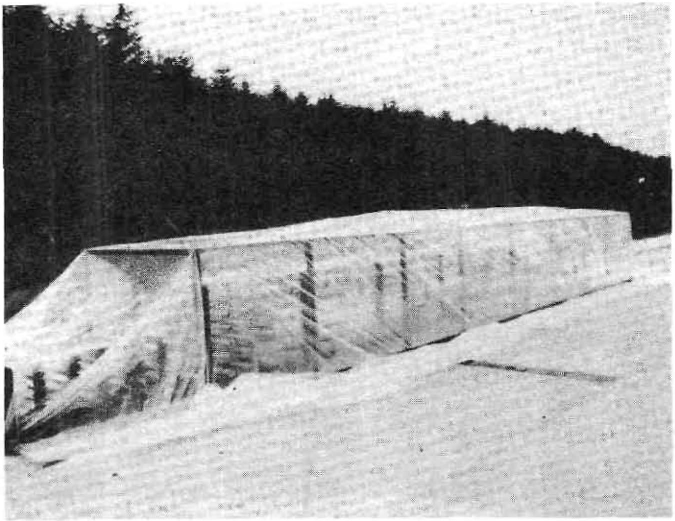
d - distance between straight section and the 1st array after bend
s - array spacing

FIG 9 EXPERIMENTAL RIG FOR THE CHANGE OF DIRECTION IN THE CONGESTED REGION

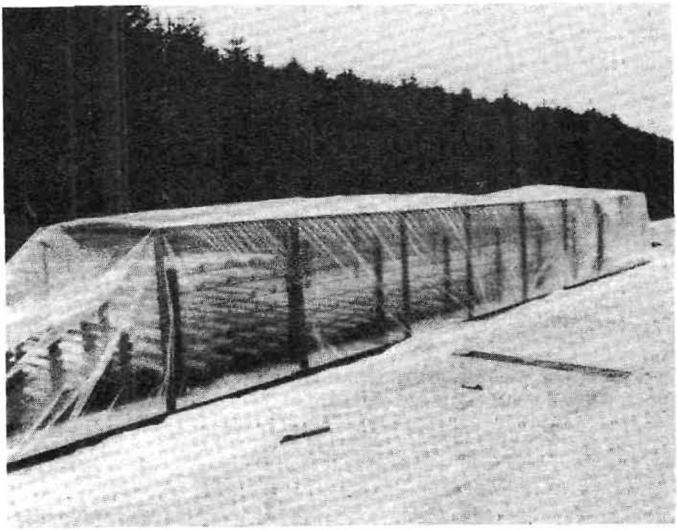


TOTAL LENGTH OF THE INCREASED FLOW
CROSS-SECTIONAL AREA CONGESTED REGION IS 10.8m

FIG 10 CHANGE IN THE CROSS - SECTIONAL AREA OF THE CONGESTED REGION OF THE SMALL SCALE ENCLOSURE

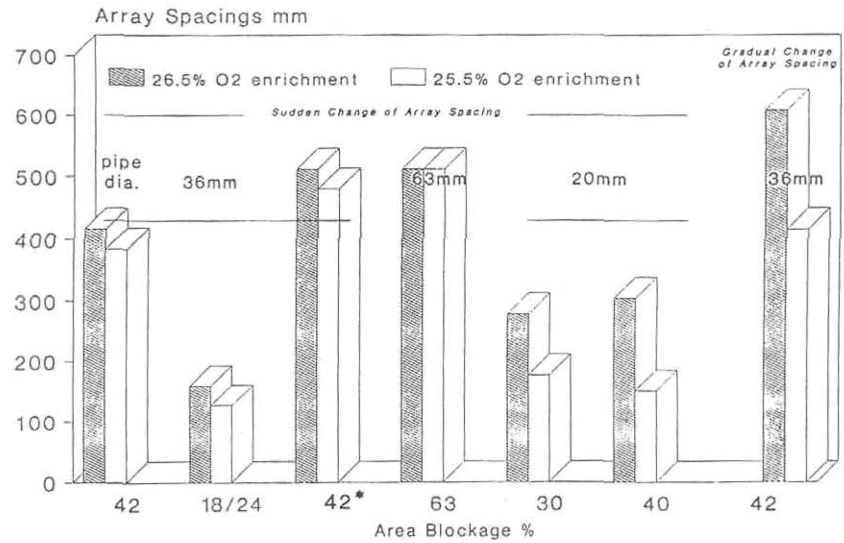


(a) OBSTACLE ARRAYS IN THE TOP HALF OF THE CONGESTED REGION



(b) OBSTACLE ARRAYS ARRAYS IN THE BOTTOM HALF OF THE CONGESTED REGION

FIG 11 HALF HEIGHT OBSTACLE ARRAYS IN THE CONGESTED REGION OF THE SMALL SCALE ENCLOSURE



* 100% area blockage on one side

FIG 12 MAXIMUM ARRAY SPACING TO SUSTAIN A HIGH SPEED FLAME